The impact of dams on floodplain geomorphology: are there any, should we care, and what should we do about it?

Philip M. Marren[1], James R. Grove[1], J. Angus Webb[2] and Michael J. Stewardson[2]

1. Department of Resource Management and Geography, The University of Melbourne, Parkville, 3010. Email: pmarren@unimelb.edu.ai

2. Department of Infrastructure Engineering, The University of Melbourne, Parkville, 3010.

Key Points

- We reviewed the impact of dams on floodplain geomorphology, using a traditional literature review and a systematic review using 'causal criteria' analysis
- We distinguish between 'passive impacts' (floodplain disconnection) and 'active impacts' (changes in geomorphological processes and functioning)
- Potential impacts include changes to: overbank flooding, scour and sedimentation, within-channel bank erosion, meander migration and cutoff frequency, and avulsion characteristics and frequency
- The causal criteria analysis found that, with the exception of reduced meander migration rates, most impacts have been too poorly documented to be confident in their impact at present
- Given practical constraints, options to mitigate dam impacts during their operational lifetime are limited to using within-channel flows to maintain meander migration and partial floodplain connectivity. We suggest that the major restoration action should be to ensure that floodplain geomorphological processes can be fully reestablished once the dam ceases to function.

Abstract

We undertook a review of the potential for dams to impact floodplain geomorphology, using both a conventional literature review and a systematic review using 'causal criteria' analysis. The literature review identified potential impacts on overbank flooding, scour and sedimentation, within-channel bank erosion, meander migration and cutoff frequency, and avulsion characteristics and frequency. The temporal scale of impacts ranged from years and decades, through to millennia. The causal criteria analysis indicated that with the exception of reduced meander migration rates, most impacts had been too poorly documented to be confident of their impact at present. We identify a distinction between 'passive impacts' (floodplain disconnection) and 'active impacts' (changes in geomorphological processes and functioning). Dams *do* impact floodplain geomorphology: many of the impacts will be subtle, and over very long timescales (1000s of years), but altered overbank sediment loads have the potential to change patterns of scour and deposition across floodplains. Further research is needed that specifically seeks to identify the impacts of dams on floodplain geomorphology, hydrology-geomorphology-vegetation interactions, and floodplain ecological response. Given the practical constraints on overbank environmental flow releases, there is relatively little that can be done to mitigate dam impacts on floodplain geomorphology. The main options include using within-channel flows to maintain meander migration and partial floodplain connectivity. We suggest that the major action should be that once dams come online, efforts should be made to prevent channel enlargement through scour, channel widening and wood removal, so that geomorphological processes can fully reestablish immediately once the dam ceases to operate.

Keywords

Dam, floodplain, flow regulation, environmental flow, environmental management, eco evidence, geomorphology

Introduction

Globally, there are over 45,000 dams, over 15 m high, impacting over half of the world's rivers (Nilsson *et al*., 2005). In Australia, there are at least 446 dams over 10 m high (Kingsford, 2000) and over 80 dams in southeast Australia with catchment areas greater than 100 km^2 (Marren *et al*., 2014). Although the diversity of dam types, sizes, upstream catchment areas, climates and channel morphologies makes it difficult to generalize, the broad impact of dams on river channels is largely understood. Changes to hydrology caused by dams typically include reduction in peak flows, shifting of the seasonality of flows and either reduced, or increased low flows when channels are used for transferring water for irrigation or hydropower purposes (Magilligan and Nislow, 2005; Graf, 2006). Within-channel geomorphological responses usually include scour, and sometimes widening downstream of the dam, for distances ranging from kilometres to tens of kilometres (Williams and Wolman, 1984). Further downstream, channels may become narrow and shallow as eroded sediment is deposited, and channels adjust to a new flow regime. This may be compounded by inputs of sediment from tributaries (Brandt, 2000; Petts and Gurnell, 2005). The impacts of dams on ecology, due to hydrological changes and disconnectivity, both within-channel, and on the floodplain, are also broadly understood (Webb *et al*., 2013), although research into environmental flow requirements to achieve ecological outcomes is ongoing (Walker, 1985; Ward & Stanford, 1995a,b; Kingsford, 2000).

In contrast to this relatively advanced understanding of the within-channel impacts of dams and flow regulation, there is a paucity of literature on the impact of dams on floodplain geomorphology. This has wider implications, as geomorphological changes on the floodplain will have impacts on floodplain vegetation and ecology (Hughes, 1997), and on the long-term functioning of floodplain wetland environments. Further, there is also potential for changes in floodplain vegetation induced by hydrological changes to feedback and produce geomorphological changes (e.g. Corenblit *et al*., 2009). Floodplain environments and habitats are controlled by feedbacks between geomorphology, hydrology and vegetation, meaning that complete understanding of the impacts of dams on floodplain ecology will only be achieved once geomorphological changes are understood and included in conceptual models. Despite the significance of the floodplain within the river corridor, there is at present a knowledge gap concerning the impacts of dams and river regulation on floodplain geomorphology. We set out to review the available literature on dam impacts on floodplain-relevant fluvial processes. Because of the paucity of literature, we also included the broader literature on geomorphic processes on undammed/unregulated floodplains, as in many cases, the controls on floodplain processes are sufficiently well understood that it should be possible to infer the consequences of changes to water and sediment fluxes downstream of a dam using fundamental geomorphological principles (e.g. Schmidt and Wilcock, 2008). The reviews focused on the impact of dams on medium to low energy lowland river meandering floodplains. This encompasses all of the floodplain types included in floodplain Types B3 and C1 of Nanson and Croke (1992) and also some types of anabranching or anastomosing floodplain, where the individual anabranches are comprised of meandering channels formed of clastic sediment. It is acknowledged that this does not encompass either the full range of floodplain types, or the full range of floodplain types which have been affected by dams.

The full findings of our review can be found in Marren *et al*. (2014), and are only outlined in brief below. Building on the conventional literature review, we used the Eco Evidence method for 'causal criteria' analysis (Norris *et al*., 2012) to test the strength of the findings identified in the literature. The Eco Evidence method is based on epidemiological techniques, and uses multiple studies drawn from the literature to build an argument for causality, weighting the contribution of each study by the quality of study design and replication. It employs the online Eco Evidence Database and desktop Eco Evidence Analyser software (Webb *et al*., 2012). The findings of the causal criteria analysis were reported in Grove et al. (2012), and are also briefly summarized below. In this paper, we build on the findings of these reviews to consider their implications for ongoing management of floodplain environments by asking whether the changes identified occur at management-relevant timescales, and whether there are any ways of incorporating floodplain geomorphology into environmental flow strategies.

The findings of Marren *et al*. (2014) and Grove *et al*. (2012)

The impacts of dams on lowland meandering river floodplain geomorphology, as developed from the review of Marren *et al*. (2014) are summarized in Figure 1. The model moves from top to bottom, corresponding to processes operating immediately, continuously, or a few years after dam closure at the top, through to long-term alteration of floodplain topography and sedimentology at the bottom, which will occur over 'geologic' timescales (100s to 1000s of years). Knowledge of, and confidence in predictions of, these processes decreases moving from 'present', through 'modern' and 'geologic' timescales.

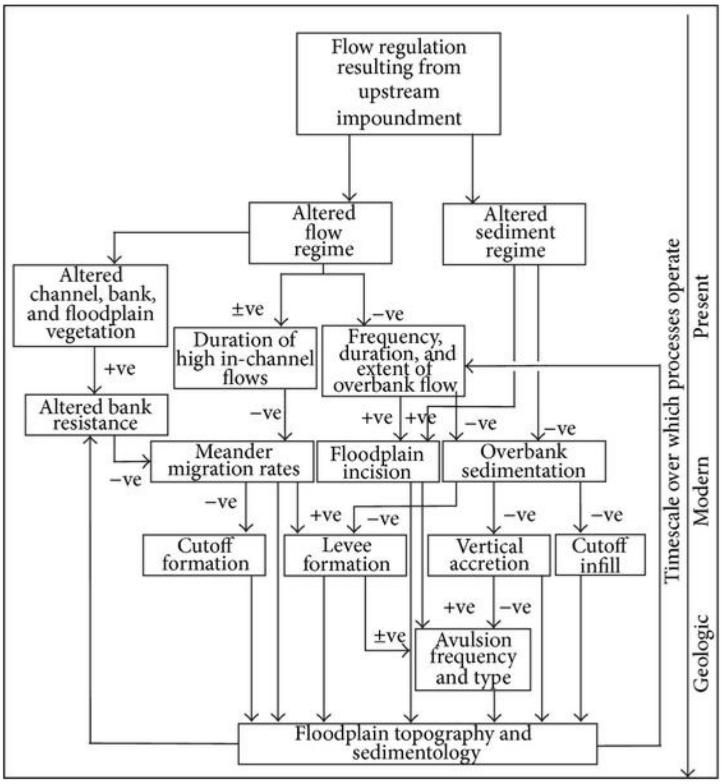

Figure 1. Conceptual model of the effects of dams on floodplain geomorphology. Timescales over which processes operate are arranged vertically through the model. +ve and –ve symbols indicate whether the changes induced by damming typically result in an increase or decrease in the rates of a particular process. Diagram reproduced from Marren *et al*. (2014).

The primary effect of dams and flow regulation is to alter the flow regime, although the exact nature of this depends on the size and purpose of individual dams. In general, the magnitude of medium to high flows will be reduced; low flows can be reduced, made less variable, or increased (Williams & Wolman, 1984; Graf, 2006). Almost all dams act as efficient sediment traps across the full range of grain sizes. Altered flow and sediment regimes impact upon both within-channel and overbank processes. Within-channel changes to bank erosion and meander migration rates alter the rate at which new floodplain deposition occurs, and reduce the frequency of meander cutoffs (Bradley & Smith, 1984). Meander migration and cutoff processes operate over 'modern' timescales which mean there are likely to be noticeable impacts within 50 to 100 years of dam construction (Shields *et al*., 2000). Overbank process changes typically include a reduction in overbank deposition, which will inhibit levee growth and decrease topographic variation across the floodplain (Renshaw *et al*., 2014). Overbank flow with reduced sediment loads may increase the potential for scour and erosion on the floodplain, particularly reentrant scour, encouraging the growth of headcut erosion, which may be a trigger for 'avulsion by incision' events (Slingerland and Smith, 2004). On the other hand, in rivers where overbank deposition rates were high, avulsion frequencies may be reduced, or avulsions might switch from being 'progadational' to 'incisional'. However, avulsions operate over very long timescales (100s to

1000s of years), so the relationship between dams and avulsion type and frequency is highly uncertain at present. Another major unknown is whether altered water and sediment fluxes will lead to a change in the relative importance of vertical and lateral accretion, which would result in a fundamental change in the overall character of the floodplain. Such changes would lead to a series of complex feedbacks with other floodplain processes (Fig. 1).

Marren *et al*. (2014) go onto consider the likely impact of dams in an 'idealised' catchment under a range of eight different dam and flow regime scenarios. These included four scenarios with a single large dam in the upper third of a catchment, and four where a second dam was placed downstream, in the floodplain reaches. Both dammed and undammed tributary scenarios were used, and the hypothetical flow regulation scenarios included one based on water supply, and one based on irrigation. Changes to floodplain processes (grouped as inundation extent, morphology, sediment and impact extent downstream) were classified as None, Low, Medium and High, and 'impact' was assessed as a change from reference condition. Using these scenarios two types of potentially negative consequences of dams were identified: 'passive' impacts were floodplain disconnection occurs, and geomorphological processes essentially stop, and 'active' impacts, where changes in geomorphological processes occur, such as a change from overbank deposition to floodplain scour.

The causal criteria analysis of Grove *et al*. (2012) was used to test the confidence in the links in the conceptual model shown in Figure 1, by assessing the 'weight of evidence' available in the literature. Only one of the hypothesized cause-effect linkages in Figure 1 was supported by the causal criteria analysis; the others had insufficient evidence to reach any strong conclusions. Reduced rates of meander migration have been demonstrated for a number of rivers, using before-after studies. Data on the rates of meander reduction can be found in Shields *et al*. (2000). The failure of the causal criteria analysis to support the other linkages is due to both the paucity of studies which have set out to study this topic, and also the nature of geomorphological evidence. The causal criteria methodology gives greater weight to studies that identify strong cause and effect relationships using before-after, control-intervention methodologies and with replicated sampling units. Geomorphological studies tend to be descriptive studies of individual sites, with less replication and statistical testing of evidence than is found in ecological studies. To mitigate this, the weightings were adjusted so that the best possible geomorphic study from the literature, for a particular question, was given the highest rating. This problem has implications for ongoing research on the geomorphological impacts of dams on floodplains, and suggests that greater emphasis should be placed on strong research design in the future.

The implications of altered floodplain geomorphology for dam management

The available evidence suggests that dams do have an impact on floodplain geomorphology, although observations of these impacts are at present limited, and our confidence in predicting these impacts is currently low. Given this state of affairs, it is reasonable to ask: should we care about dam impacts on floodplain geomorphology? And is there anything we should be doing, or should change which would help mitigate these impacts?

Firstly, there is the question of time. Over the lifetime of a 'typical' dam, which might be 300-500 years, some changes can be expected, whilst others may not have happened before the dam is removed. Clearly, the primary focus should be on those processes that are highly likely over the lifetime of a dam, such as reductions in meander migration rates. Secondly, there is the distinction between passive and active impacts to consider. For passive impacts, it may be possible that geomorphological floodplain processes can be put 'on hold' for the duration of the dammed period, and that compared to the geological lifetime of the floodplain, the dam is irrelevant. For active impacts, such as increasing floodplain scour during flood events, it is more reasonable to suggest that actions to mitigate these impacts might be taken.

Preventing active impacts is closely related to the problem identified above of preventing a change in the relative importance of vertical and lateral accretion. Normal meander migration usually removes more sediment from the eroding outer banks than is deposited on point bars, with the sediment budget balanced by deposition elsewhere on the floodplain (i.e. as overbank deposition) (Lauer and Parker, 2008). Reducing the amount of time that the river spends overbank, or reducing the amount of sediment entering a dammed reach from upstream will disrupt the equilibrium between water and sediment flux. For these changes to be mitigated, Marren *et al*. (2014) suggested that an 'environmental sediment regime' should be considered alongside the usual environmental flow regime. In practical terms, this would require information on pre-dam suspended and bedload sediment loads across a range of flow magnitudes, in order that these could be mimicked in environmental flow releases, or augmented during natural floods where the majority of sediment is usually trapped in the dam. At present, the information required to do this is lacking for most rivers, and the means of delivering the appropriate size and volume of sediment to the river downstream of the dam, is not available. As such, this is not a practical solution for the immediate future, but may indicate the direction of future research and management efforts.

Restoring floodplain geomorphological functioning has to be considered within the framework of real-world practicalities and limitations. For instance, overbank sedimentation processes can only occur during floods large enough to inundate a significant part of the floodplain. There are infrastructure-based limitations to the size of environmental flows that can be released from many dams, and there is rarely any provision to release sediment from the dam with these flows. Also, flows large enough to inundate the floodplain will meet opposition where the inundated extent includes private land and buildings. It is therefore practical to ask if there is anything that can be done to maintain floodplain geomorphological functioning using the usual range of within-channel flow releases?

The answer is yes; some things can be achieved by within-channel flows. For instance, high within-bank flows of sufficient duration may be able to maintain meander bend migration rates even in the absence of larger floods of shorter duration. Also, providing sufficient provision is given to maintaining or creating connectivity between anabranches and oxbow lakes (meander cutoffs), partial inundation of the floodplain may be possible (Fig. 2, especially panel C). Such 'flow pulses' have been shown to provide strong ecological benefits (Tockner *et al*., 2000), but may also have significant benefits in terms of maintaining geomorphological functioning. In sand and gravel-dominated floodplains, high within-channel flows may also raise floodplain groundwater levels, although this effect is reduced in floodplains dominated by fine-grained sediments and where depressions such as oxbows are lined with clay, preventing groundwater-surface water interactions (Lewandowski *et al*., 2009).

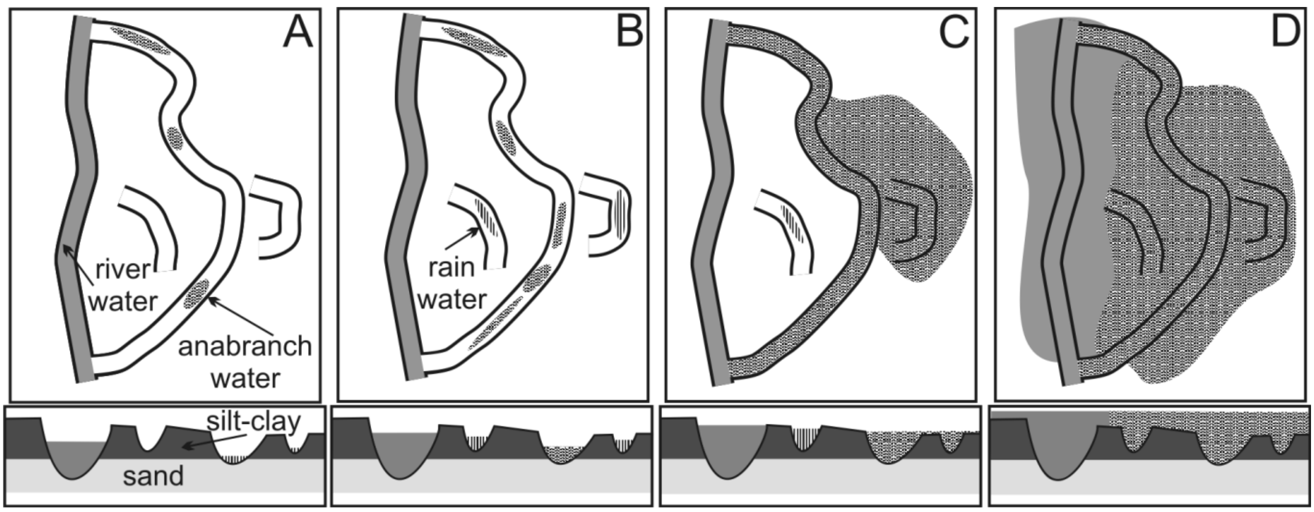

Figure 2. Conceptual model of inundation of anabranching river floodplains, based on the Ovens River, Victoria. At bankfull discharge anabranch and cutoff connectivity allows partial inundation and floodplain integration (2C). Diagram based on Marren and Woods (2011).

Although there are some outcomes that can be achieved using within-channel environmental flow releases, options for preventing both passive and active geomorphological floodplain impacts are generally limited. Instead, we propose that the most useful management action that can be taken is to preserve channel-floodplain connectivity so that once the dam has reached the end of its functional period, normal geomorphological processes can be resumed immediately. In practical terms, what this means is that from the outset following dam closure, excessive channel enlargement (via bed scour, bank erosion and woody debris removal) should be minimized, as increasing channel capacity will reduce the frequency of overbank flows even if the natural flow regime is later restored. Similarly, artificial barriers to floodplain connectivity such as regulators and levees should be designed so that they can easily be decommissioned once upstream flow regulation ceases.

Conclusions

Based on our literature review and causal criteria analysis, we conclude that there are a number of ways in which dams are impacting floodplain geomorphology, operating on a range of timescales from the 'present', through 'modern' and 'geologic'. Impacts are both passive (floodplain disconnection) and active (changes in floodplain processes). Given the practical limitations of environmental flow regimes, in terms of maximum possible discharges and the difficulties in restoring the sediment regime, there are only a small number of practical actions that can be taken to mitigate the impact of dams on floodplain geomorphology. These are mostly focused on maintaining rates of channel migration and maintaining partial floodplain connectivity. We suggest that it is more useful to ensure that actions in the present day do not impede long term functionality of the floodplain, so that when a natural flow regime is eventually restored, it is still possible for the floodplain to function naturally, and floodplain geomorphological processes can be 'switched on' again. Relevant actions include preventing channel scour and enlargement, maintaining a natural wood load in the channel, and ensuring that floodplain infrastructure will not inhibit floodplain functionality when it is no longer needed.

Acknowledgments

This work was originally carried out as part of the eWater CRC project 'Ecological Management and Restoration', particularly the Northern Victorian Applications project.

References

Bradley, C., & D. G. Smith, D.G. 1984. Meandering channel response to altered flow regime: Milk River, Alberta and Montana. *Water Resources Research*, 20, 1913–1920.

Brandt, S.A. (2000). Classification of geomorphological effects downstream of dams. *Catena*, 40, 375-401,

Corenblit, D., Steiger, J., Gurnell, A.M., Tabacchi, E. & Roques, L. (2009). Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Processes and Landforms*, 34, 1790-1810.

Graf, W.L. (2006). Downstream hydraulic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79, 336-360.

Grove, J.R., Webb, J.A., Marren, P.M., Stewardson, M.J., Wealands, S. (2012). High and Dry: An investigation using the Causal Criteria methodology to investigate the effects of regulation, and subsequent environmental flows, on floodplain geomorphology. *Wetlands*, 32, 215-224.

Hughes, F.M.R. (1997). Floodplain biogeomorphology. *Progress in Physical Geography*, 21, 501-529.

Kingsford, R.T. (2000). Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology*, 25, 109-127.

Lauer, J.W. & Parker, G. (2008). Net local removal of floodplain sediment by river meander migration. *Geomorphology*, 96, 123-149.

Lewandowski, J., Lischeid, G. & Nutzmann, G. (2009). Drivers of water level fluctuations and hydrological exchange between groundwater and surface water at the lowland River Spree (Germany): Field study and statistical analyses. *Hydrological Processes*, 23, 2117-2128.

Magilligan, F.J. & Nislow, K.H. (2005). Changes in hydraulic regime by dams. *Geomorphology*, 71, 61-78.

Marren, P.M., Grove, J.R., Webb, J.A. & Stewardson, M.J. (2014). The potential for dams to impact lowland meandering river floodplain geomorphology. *The Scientific World Journal* vol. 2014, Article ID 309673, 24 pages. doi: 10.1155/2014/309673.

Marren, P.M. & Woods, K.L.M. (2011). Inundation of anabranching river flood plain wetlands: the Ovens River, Victoria, Australia. In: C. Abesser, Nützmann, M.C. Hill, Blöschl & E. Lakshmanan (eds.), *Conceptual and Modelling Studies of Integrated Groundwater, Surface Water, and Ecological Systems*. IAHS Publ. 345, 229-234.

Nanson, G.C. & Croke, J.C. 1992. A genetic classification of floodplains. *Geomorphology*, 4, 459–486.

Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science*, 308 (5720), 405–408.

Norris, R.H., Webb, J.A., Nichols, S.J., Stewardson, M.J. & Harrison, E.T. (2012). Analyzing cause and effect in environmental assessments: using weighted evidence from the literature. *Freshwater Science*, 31, 5-21.

Petts, G.E. & Gurnell, A.M. (2005). Dams and geomorphology: research progress and future directions. *Geomorphology*, 71, 27-47.

Renshaw, C.E., Abengoza, K., Magilligan, F.J., Dade, W.B. &. Landis, J.D. 2014. Impact of flow regulation on near-channel floodplain sedimentation. *Geomorphology*, 205, 120–127.

Schmidt, J.C. & Wilcock, P.R. (2008). Metrics for assessing the downstream effects of dams. *Water Resources Research*, 44, W04404, doi:10.1029/2006WR005092,

Shields, F.D., Simon, A. & Steffen, L.J. (2000). Reservoir effects on downstream river channel migration. *Environmental Conservation*, 27, 54-66.

Slingerland, R. & Smith, N.D. (2004). River avulsions and their deposits. *Annual Review of Earth and Planetary Sciences*, 32, 257-285.

Tockner, K., Malard, F. & Ward, J.V. (2000). An extension of the flood pulse concept. *Hydrological Processes*, 14, 2861-2883.

Walker, K.F. (1985). A review of the ecological effects of river regulation in Australia. *Hydrobiologia*, 125, 111-129.

Ward, J.V., & Stanford, J.A. (1995a). The serial discontinuity concept: extending the model to floodplain rivers. *Regulated Rivers*, 10, 159-168.

Ward, J.V. & Stanford, J.A. (1995b). Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers*, 11, 105-119.

Webb, J.A., Miller, K.A., King, E.L., de Little, S.C., Stewardson, M.J., Zimmerman, J.K.H. & Poff, N.L. (2013). Squeezing the most out of existing literature: a systematic re-analysis of published evidence on ecological responses to altered flows. *Freshwater Biology*, 58, 2439-2451.

Webb, J.A., Norris, R.H., Nichols, S.J., Stewardson, M.J., Wealands, S.R. & Lea, P. (2012). Ecological responses to flow alteration: assessing causal relationships with eco evidence. *Wetlands*, 32, 203-213.

Williams, G.P. & Wolman, M.G. (1984). *Downstream effects of dams on alluvial rivers*. United States Geological Survey, Professional Paper 1286.